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A New Immiscible Water Alternating Gas (I-WAG) Scheme for Improvement of Displacement Efficiency in Dipping Reservoirs

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Abstract

The success of the hydrocarbon recovery improvement via water alternating gas injection is closely related to the microscopic displacement and macroscopic sweep efficiencies by maximizing the three-phase zones and optimizing force balance. Although the WAG process improves the sweep efficiency by controlling the mobility of gas in the cycle of water injection, the improvement will not be optimum in dipping reservoirs. In such reservoirs, a water and gas injection scheme plays an important role in the optimization of sweep and displacement efficiencies. In this paper, the efficiency of various WAG injection schemes toward the improvement of recovery factor will be presented. A new injection scheme is proposed. In the new proposed scheme, water is injected from down dip, and gas is injected from up dip in the first cycle. In the second cycle, gas is injected from down dip, and water is injected from up dip. Water and gas injection locations will alternatively change in each cycle of injection. Different parameters are studied including mobility ratio, anisotropy ratio (kv/kh), injection rate, WAG injection cycle. The results show that the proposed scheme has a significant improvement on the displacement efficiency and three-phase zone size and hence yields higher hydrocarbon recovery.

1. Introduction

Most WAG injection was initially proposed as a method to improve sweep efficiency of gas injection by using the water to control the mobility of gas and to stabilize the front. Since microscopic displacement of the oil by gas is normally better than water, WAG injection combines the improved displacement efficiency of the gas flooding with an improved macroscopic sweep of water injection. This potentially improves the hydrocarbon recovery compared to a pure water or pure gas injection and results in less residual oil left in the reservoir.

WAG injection has been applied since the early 1960's [1]. The first field application of WAG process took place in the North Pembina field in Alberta, Canada, in 1956 and1957. There were not reported any injectivity abnormalities in this field [2]. Since then, WAG injection has been applied with success in

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most field trials. The majority of the fields were located in Canada, U.S. and former USSR, but recently there are some fields in North Sea region and South Asia under WAG implementation and study [1].

WAG injection can be classified as miscible and immiscible injection. If the gas injection happens above Minimum Miscible Pressure (MMP), the process is to be called miscible WAG, whereas if injection of the gas is below the MMP, the process is called immiscible WAG. It may be difficult to distinguish between miscible and immiscible WAG injections in the entire flood area from the front to the tail because the WAG process might undergo multi-contact miscibility under vaporizing and/or condensing gas drive. Both miscible and immiscible injections have been applied for WAG injections with different types of gas. In this study, the focus is more on the immiscible gas injection.

In this paper, different schemes of immiscible WAG (I-WAG) injection are considered to investigate the effect of each scheme on the recovery factor for dipping reservoirs. The injection schemes are typically determined by WAG related parameters (e.g., WAG ratio, slug size, etc.) and should be subjected to special design for particular reservoir conditions. Therefore different design parameters such as mobility ratio, heterogeneity aspect ratio, location of injection, injection rate, WAG ratio and WAG cycle need to be studied for each scheme. A new injection scheme, which improves the oil recovery factor for dipping reservoirs, is proposed in this study. In the new scheme, water is injected down dip and gas is injected up dip in the first cycle and in the second cycle water is injected up dip and gas will be injected down dip and so on. The new injection scheme can effectively improve the three phase zone and optimize the displacement efficiency leading to higher recovery factor.

An extensive literature review of WAG injection projects and injectivity abnormality in the CO_2 process was done by Rogers and Grigg in 2001. They summarized 23 projects of WAG injection in U.S. and studied different parameters, which affect the improvement of recovery factor and infectivity in WAG schemes. The displacement mechanism in the WAG process occurs in a three-phase regime. The cyclic nature of the process creates a combination of imbibition and drainage processes. Optimum conditions of oil displacement by WAG processes are achieved if the gas and water have equal velocity in the reservoir. The optimum WAG design is different for different reservoirs and needs to be studied on case-by-case basis and possibly fine-tuned for patterns within the reservoir. There are a number of different WAG schemes to optimize the hydrocarbon recovery. Important technical factors effecting WAG performance that have been identified are: heterogeneity, wettability, fluid properties, miscibility condition, injection techniques, WAG parameters, physical dispersion and flow geometry [2].

MousaviMirkalaei et al. (2012) have studied the parameters affecting displacement efficiency in CO_2-WAG injection. They studied different parameters such as pressure, temperature, oil composition, fluid properties, IFT, hysteresis, and reservoir pore configuration. In miscible CO_2 injection diffusion phenomena increase microscopic displacement efficiency while dispersion decreases microscopic displacement efficiency. Also, low injection rate and high residency time will improve the microscopic displacement efficiency because of swelling, viscosity and surface tension reduction [3].

In immiscible CO_2-WAG injection microscopic displacement efficiency mostly related to relative permeability and capillary pressure hysteresis which are depended to pore geometry and wettability of the rock indirectly. WAG parameters (WAG ratio, slug size, WAG cycle), mobility ratio, viscous to gravity ratio, injection strategy and reservoir heterogeneity are the macroscopic factors. The result of this study showed the WAG injection scheme has a significant effect of macroscopic displacement efficiency and could yield to higher hydrocarbon recovery [3, 4].

Based on the literatures, WAG injection provides benefits to improve displacement efficiency and sweep efficiency by controlling the mobility of gas and stabilizing the front of flood. However, several technical, economical, and operational issues should be studied before implementation of a WAG projects. Technical parameters include rock pore geometry and pore structure, reservoir dipping, pressure, temperature, fluid and rock properties, saturation history of rock-fluid system before WAG injection, and WAG related parameters (i.e., WAG ratio, viscous to gravity force, slug size, WAG cycle, injection rate and injection place). Other principle requirements for a suitable WAG process are low cost injection, favorable reservoir conditions and operational feasibility. Running pilots before implementation of any large scale WAG project is advised, no matter what the results from the reservoir models indicate. The design and location of a field pilot test should be technically and economically sound for the results and conclusions of the pilot test to be applicable to the entire reservoir. Monitoring of different constrains such as productions and injection rate, bottom-hole pressure for injection and product well and tracer-if applicable- and injectivity test are the key factors in implementation phase [5-9].

2. Adopted methodology in this study

The objective of this study is to conduct a theoretical investigation and simulation study of different I-WAG schemes to optimize the displacement efficiency and improve recovery factor. Different schemes of I-WAG process are studied by designing parameters of the process. One of the most important parameter is dipping (or inclination) of the reservoirs, which affect the sweep, microscopic, and overall the displacement efficiency. For stratified reservoir, there are some analytical models [10, 11] and also simulation studies [12-14], which explained about the performance of WAG injection considering different parameters. Heterogeneous reservoirs, however, has more complexity and analytical approaches may not potentially simulate the applied processes in the reservoir. Therefore, it might be necessary to consider a numerical simulation study to investigate the effect of different parameters and different schemes on recovery factor. As mentioned in the previous section, different injection schemes have been reported in the literature, such as gas injection up-dip and water injection down-dip, vice versa, for the entire cycles of the I-WAG . Here, we propose a new injection scheme which is gas injection in up-dip and water injection in down-dip in the first cycle of WAG injection and gas injection down-dip and water injection up-dip in the second cycle and so on. We believe this new scheme will have better displacement because of increasing the three phase zone in up-dip and down-dip together while in other schemes most of the swept region will be two phases, and the displacement efficiency of three phase region always are more. In the other hand because of mobility control up-dip and down-dip, the sweep area will be increased.

A simple synthetic black oil sector model has been used to conduct the first part of this study. The effects of various schemes on the sweep and displacement efficiency have been studied in this model. Table 1 shows the different schemes of I-WAG with respect to injection location, which are considered in this study. An extensive sensitive analysis was performed to determine the effect of different input and WAG parameters on recovery factor. The parameters that were considered for the sensitivity analysis include heterogeneity aspect ratio (kv/kh), mobility ratio, WAG ratio, injection rate, and WAG cycle.

Table 1. Different studied schemes of I-WAG with respect to injection locations

Schemes	1st cycle injection		2nd cycle injection	
	Water	**Gas**	**Water**	**Gas**
Scheme I	Down dip	Up dip	Down dip	Up dip
Scheme II	Up dip	Down dip	Up dip	Down dip
scheme III	Down dip	Up dip	Up dip	Down dip

The findings of this part of study are then evaluated in a three dimensional heterogeneous sector model of a reservoir from an oil field in Malaysia. Sensitivity analysis has been conducted for the simple model of homogeneous dipping reservoir (to be described in the next section) for different parameters and the best schemes with considering different parameters such as mobility ratio, location of the water and the gas injectors, injection rate, WAG injection cycle. This is to find the optimum value for better displacement efficiency and the optimal injection schemes in the real reservoir model to improve the recovery factor.

3. Sector Model Description

In this section, the two synthetic models and one real field sector model, which have been used in this study, are described.

3.1. Synthetic Sector Model

A simple synthetic model, homogeneous, two-dimensional with dipping layered reservoir is used for the first part of simulation study. The complexity of the reservoir model was kept to a minimum in attempt to see clearly the effect of injection schemes on a dipping reservoir.

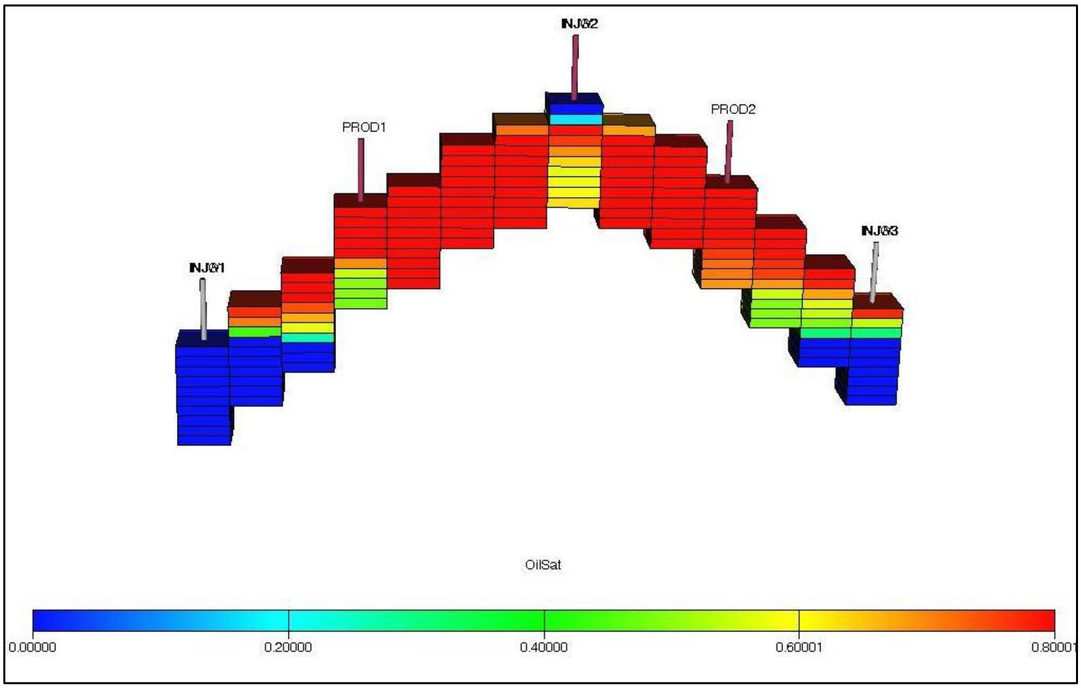

Figure 1. Three-dimensional view of the synthetic sector model

Figure 1 shows the three dimensional view of the synthetic sector model. The porosity is 0.15 and horizontal permeability is 100 md, which coincides with the average porosity and permeability of the realistic model. The sector model has 14 × 1 × 10 grid blocks with the dimension of 500 × 500 × 50 ft and total pore volume of about 46.75 × 106 reservoir barrels.

Table 2. Data used in synthetic model

Parameter	Value
Porosity	15%
Horizontal Permeability	100 md
Vertical Permeability	10 md
Dimension	14 × 1 × 10
Pore Volume	46.75 × 106 RB
Initial oil in place	17.9 × 106 STB
Initial fluid gravity at surface o/w/g	40/1.16/0.824 API/SG
Initial fluid viscosity at ref. press. o/w/g	0.6 / 0.3 / 0.04 cp
Initial (Ref.) Reservoir Pressure at 10,900 ft	5600 psi
Rock/Water compressibility	3.5 × 10-6 / 3.0× 10-6 psi-1

Table 2 presents the other relevant fluid and rock property data and initial reference pressure at a datum depth of 10,900 ft, which used in this model. Figures 2 and 3 show the relative permeability curves for water/oil and oil/gas system which are used for this synthetic model. The rock is assumed to be water wet. For the hysteresis model we used the Larsen (Larsen and Skauge 1999) which is available in the simulation software [15].

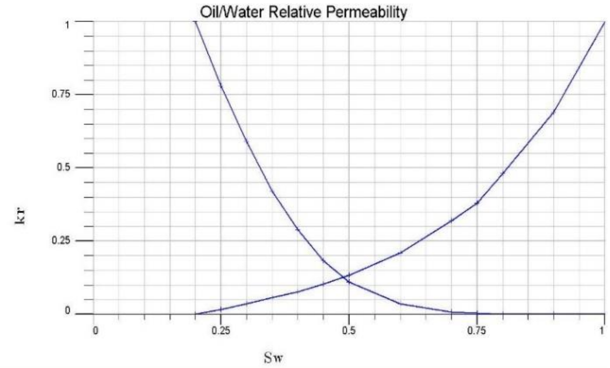

Figure 2. Water-oil relative permeability curves

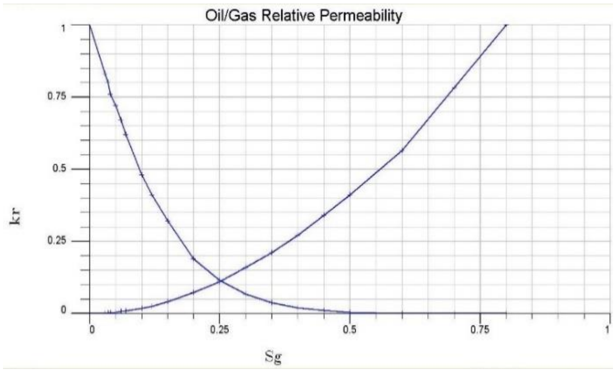

Figure 3. Oil-gas relative permeability curves

3.2. Real Field Sector Model

A sector model of an actual field in Malaysia is subjected to extend the result of simple model and study the effect of different WAG schemes on displacement efficiency and recovery factor. The geometry of the sector model is characterized by a dome with a gas cap in the center. It contains some sandstone layers and shale. The top of the reservoir is at a depth of 8215 ft. The average reservoir thickness is 192 ft with average net to gross (NTG) of about 0.94. The reservoir is discretized into

269 × 19 × 70 grid blocks of which 273,461 blocks are active. The average x and y dimension of each block is 100 ft and 82 ft respectively. The average porosity (Ø) is 15%, the average horizontal permeability (kh) is 195 md the average vertical permeability (kv) is 36 md. A map of the heterogeneous absolute permeability field is shown in Figure 4. Since we are using the real sector model of a reservoir so there are different rock types with different relative permeability and capillary pressure for each rock. Figures 5, 6, and 7 show the relative permeability of oil/water, oil/gas, and oil/water capillary pressure curves, respectively. The reservoir pore volume is about 88e+06 reservoir barrels with initial oil in place of about 16.7e+06 reservoir barrels and an initial reservoir pressure of 3970 psia at datum depth. The initial fluid distribution map is shown in Figure 8. Production from this field started in September 1968. The history of the production for this field has been history matched till December 2007. We used the model to predict the production from this date until January 2020. We kept the production well locations and define 2 new wells for WAG injection. The locations of these two new wells are up deep and down deep. WAG injection is started from April 2010 and continues for 10 years. This sector model has two injection wells for water and gas injection and six production wells, open to different layers of the reservoir. The production wells operate and are controlled by fixed bottom-hole pressure. The injection wells are rate controlled, and inject 300 rb/day each at bottom-hole pressure of 5000 psi for water and 750 Mscf/day at 1600 psi for gas.

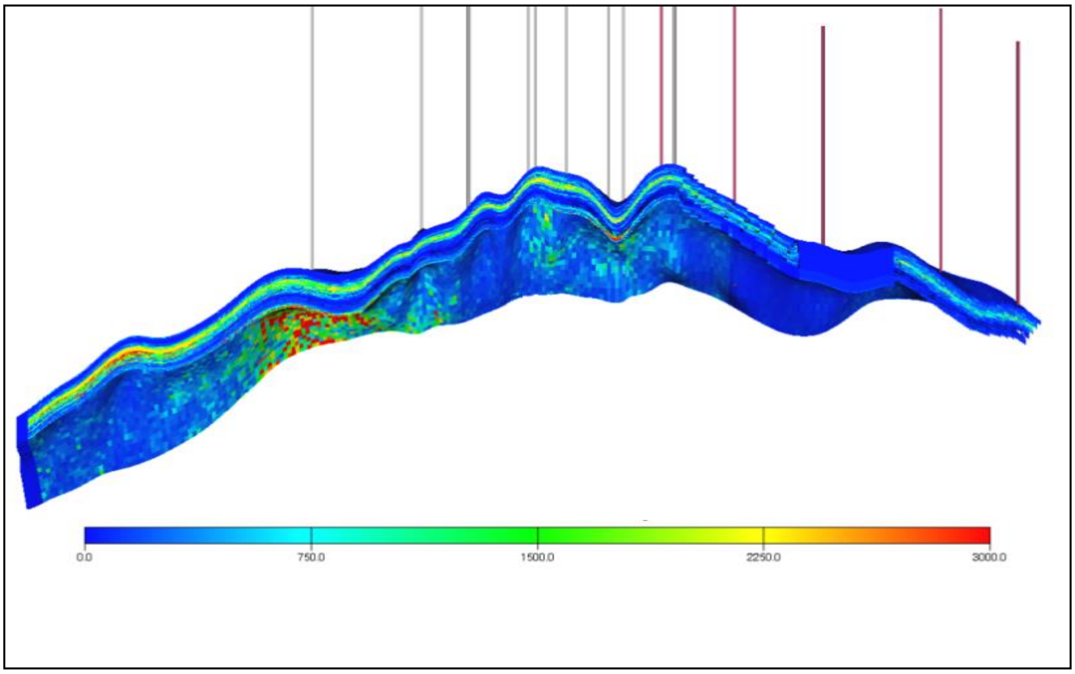

Figure 4. Horizontal permeability distribution (md)

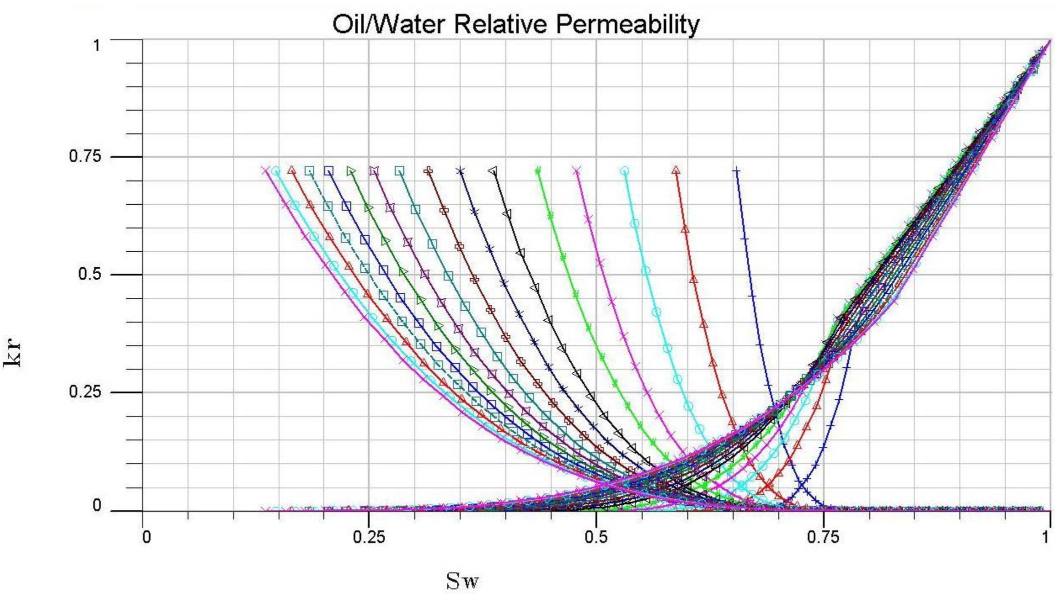

Figure 5. Water-oil relative permeability curves for real sector model

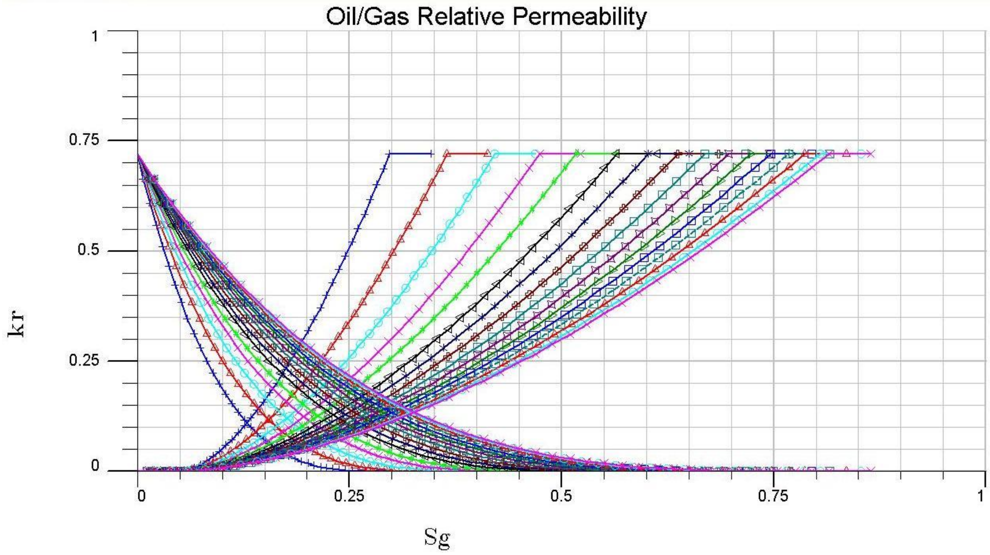

Figure 6. Oil-gas relative permeability curves for real sector model

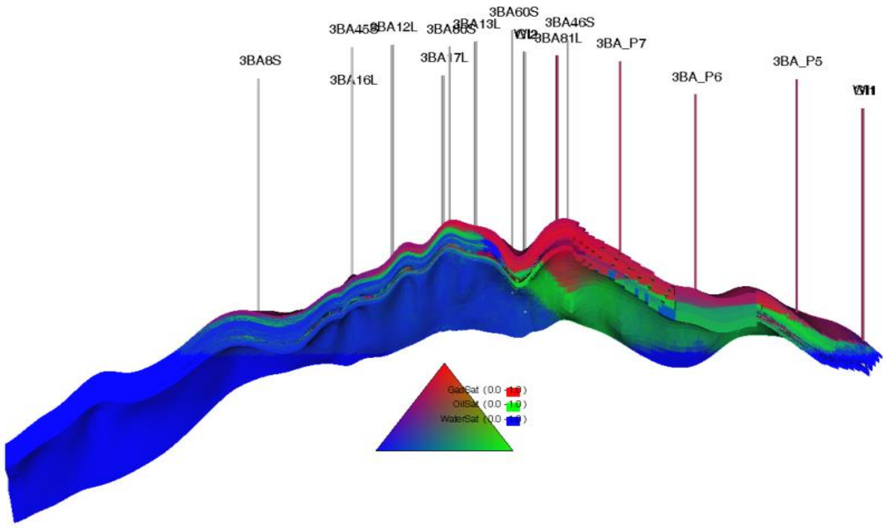

Figure 7. Initial fluid distribution and location of the wells

4. Results and Discussion

The above mentioned simulation models were run with a commercial numerical simulator and the result of each model are described and discussed as below:

4.1. Synthetic model

Effect of different parameters is investigated in simple synthetic model including kv/kh, water to oil mobility ratio, injection rate and WAG cycle.

4.1.1. Effect of heterogeneity aspect ratio kv/kh

Heterogeneity aspect (or anisotropy) indicates the extend of vertical communication between layers in the reservoir. In WAG injection process, a high value of kv/kh means both injection fluids (water and gas) can move vertically downward and upward easily in the reservoir. Therefore, phase segregation will occur very fast, and mobility control and displacement efficiency will be unfavorable. In the lack of experimental data, generally the assumption of kv/kh = 0 is made 0.1, and this not unrealistic for sandstone type reservoirs. Since, practically very low and very high value of kv/kh is not acceptable, we run the simulation for different kv/kh = 0.07, 0.1, and 0.5 to see the effect of the aspect ratio on each scheme of injection.

Figure 9 shows the incremental oil recovery versus pore volume of injection for different WAG schemes for kv/kh=0.07. Scheme III which has alternate injection of gas and water from up dip and down dip (see Table 1) has around 15% higher recovery compares to the other two schemes. In the low kv/kh, injected fluid cannot move vertically and the water cannot control the mobility of gas. In this case, the gas fingering and override will occur and cause low displacement efficiency and consequently low recovery. When we change the injection place from down dip to up dip in Scheme III, saturation of gas and water will increase and it caused mobility control of each phase, which lead to increase in recovery.

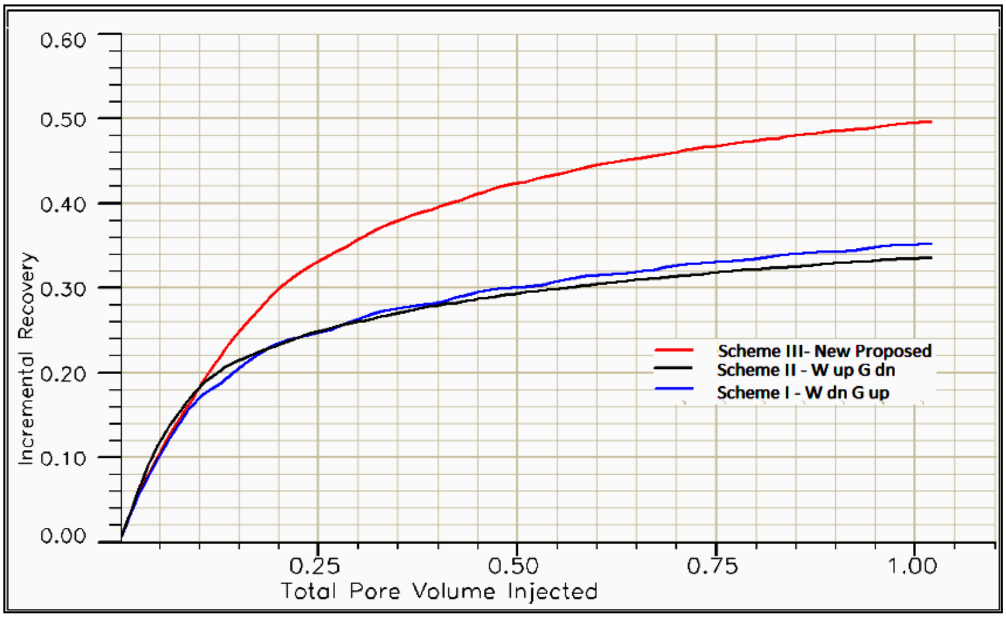

Figure8. Incremental recovery vs. PV injected for different WAG schemes for kv/kh= 0.07

Table 3 summarizes the results for the incremental oil recovery obtained from the simulation study for different values of the kv/kh for each scheme of Table 1. For kv/kh=0.1, due to layer communication in this case, the difference between incremental recovery for Scheme III and two other schemes (Scheme I and Scheme II) is less compared to kv/kh =0.07 (around 6%).

Table 3. Effect of heterogeneity aspect ratio on incremental recovery for each scheme

kv/kh	Scheme I	Scheme II	Scheme III
0.07	36%	34%	50%
0. 1	44%	42%	50%
0.5	44%	46%	54%

The incremental oil recovery for kv/kh = 0.5 for all schemes have been improved compare to previous case (kv/kh =0.1), but not by the same ratio. For Scheme III, this increase is about 4% while for Scheme I and Scheme II is around 10%. However the recovery for Scheme III is not as sensitive as the recoveries for the other schemes to the increase in kv/kh. The main reason of improvement in WAG recovery is the gas mobility control (for better displacement efficiency). In Scheme III, alternately changing the place of injection controls the gas mobility effectively. For Schemes I and II, for which the injection place is fixed, increasing the value of kv/kh improves the recovery but, after a certain limit, the effect will be less significant because of the phase segregation. Mobility control mechanism due to three-phase flow will not contribute to the oil displacement anymore. The proposed scheme shows better hydrocarbon recovery results in all of the considered values of the kv/kh ratio.

4.1.2. Effect of water to oil mobility ratio

Here we define the mobility ration of water to oil at the end point relative permeability. We chose three different mobility ratio (M = 0.5, 1 and 20) to see the effect of unfavorable mobility ratio on WAG recovery. Figure 10 shows the incremental recovery vs. pore volume injected for three different values of mobility ratio for Scheme III. High mobility ratio increases the potential of unstable front and it may cause fast segregation of gas and water, which may cause early breakthrough in the reservoir and leaving oil in un-swept. When mobility ratio decreases more stable displacement front caused the injected fluids invade larger area in the reservoir. Thus, unfavorable mobility ratio can reduce oil recovery significantly in WAG process due to early gas/water breakthrough and less sweep efficiency. In Scheme III water injection from up dip move downward reaching and will slowdown the gas to move upward and leave un-swept area.

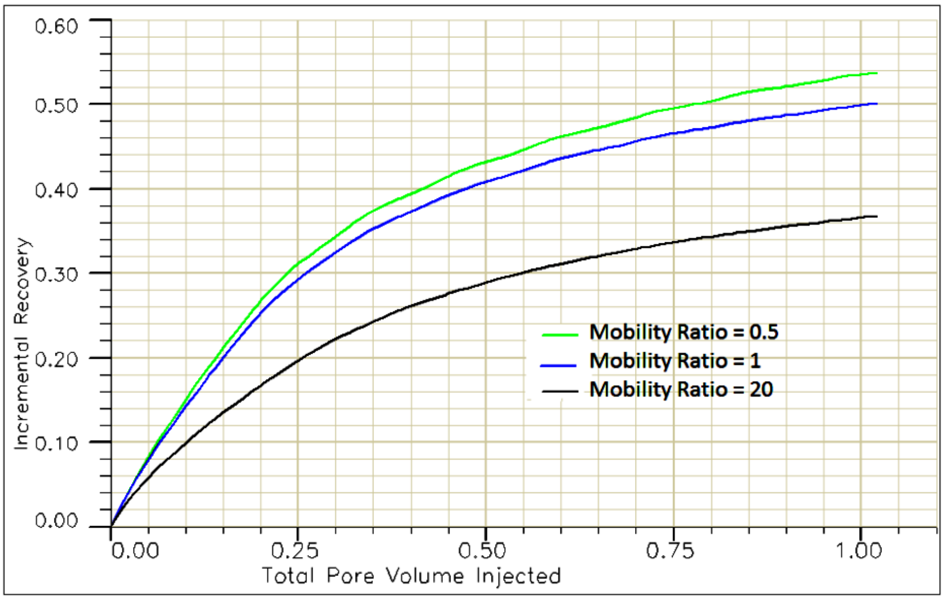

Figure 9. Incremental recovery vs. PV injected for different mobility ration for Scheme III

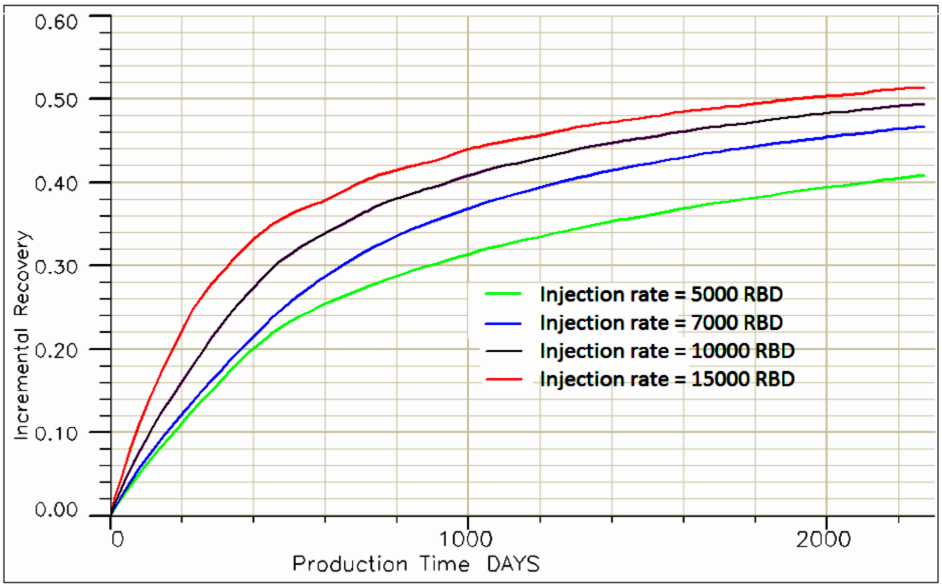

Figure 10. Incremental recovery vs. production time for different injection rate for Scheme III

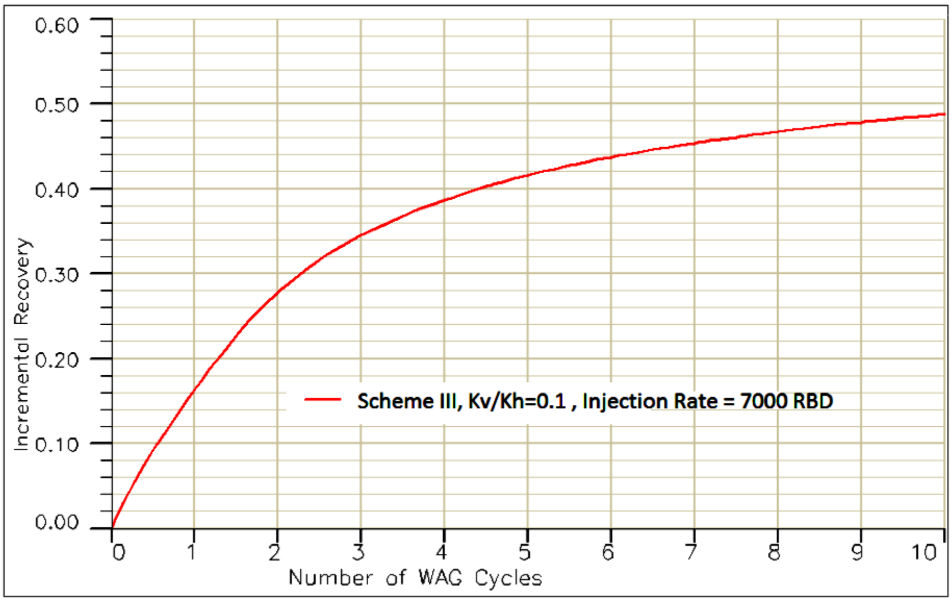

Figure 11. Incremental recovery vs. number of WAG cycles for Scheme III

4.1.3. Effect of injection rate

The simulation has been run using four different injection rates (5000, 7000, 10000 and 15000 RB/D). Figure 11 shows that the higher the injection rate the higher the recovery factor. However, the increase in injection rate will decrease the difference between WAG recoveries for Scheme III as the rate increases. Injection rate increase can potentially cause phase segregation and gas & water will be segregated early in the reservoir. Consequently displacement efficiency will be lower.

4.1.4. Effect of number of WAG cycles

Figure 12 shows the result of recovery for different number of WAG cycles for Scheme III. One may conclude that the most efficiency of WAG cycles is in initial cycles. After a few cycles (3 or 4), there is a small improvement in incremental recovery and this difference will be less as we further increase the number of cycles. The number of efficient cycles depends on the size of the reservoir, meaning that for huge reservoir even high number of cycle still can improve the recovery significantly.

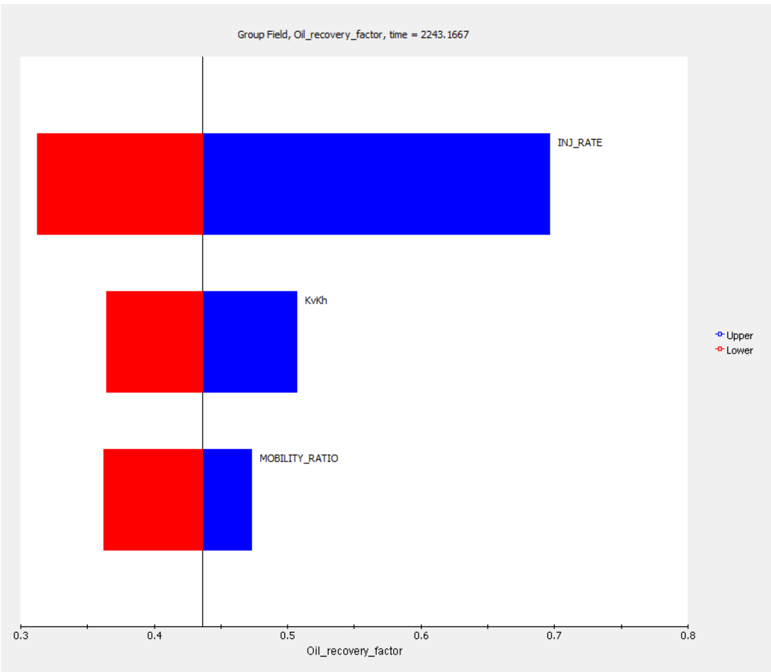

Figure 12. Sensitivity analysis result in Tornado chart

4.1.5. Sensitivity analysis

Sensitivity analysis was conducted to evaluate the impact of different parameters on the final hydrocarbon recovery results. To be more conscious about the impact of each parameter on the oil recovery the important parameters have been selected as modifiers in an experimental design practice with minimum, most likely and maximum values as presented in Table 4. The most likely values have been taken from the mostly referred values. The first sets of sensitivities were run to investigate the impact of each parameter on overall recovery factor of the model.

As can be seen in Figure 13 from analysis of results in the tornado chart, all the parameters show a positive correlation which means if increases the injection rate for instance the recovery factor will increases. The most influential parameter is the injection rate and after that permeability aspect ratio. The results have shown that this parameter is the most effective parameter on the total hydrocarbon recovery.

4.2. Real Field Sector Model

Here we used the findings from the result of sensitivity analysis parameters, which have been done in simple synthetic model to find the optimum value for each parameter in the real field sector model. The mobility ratio between oil and water is about 0.5 with a slug size of 0.5e-3 pore volumes, which was found to be an optimum operation scheme. The WAG cycle is 180 days of water and 90 days of gas injection for a total simulation time over 4000 days (10 yrs).

The real sector model was run for four different scenarios. Then, the results obtained were compared in terms of the recovery factor prediction for ten years. The first scenario is the base case, which continues production from reservoir without WAG injection. The second scenario is WAG injection using Scheme I, i.e., water injection down dip and gas injection up dip, and the third scenario is WAG injection using Scheme II, i.e., water injection up dip and gas injection down dip. The last (fourth) scenario is WAG injection using the newly proposed Scheme III, i.e., water injection down dip and gas injection up dip in first half cycle and water injection up dip and gas injection down dip in the second half cycle and so on.

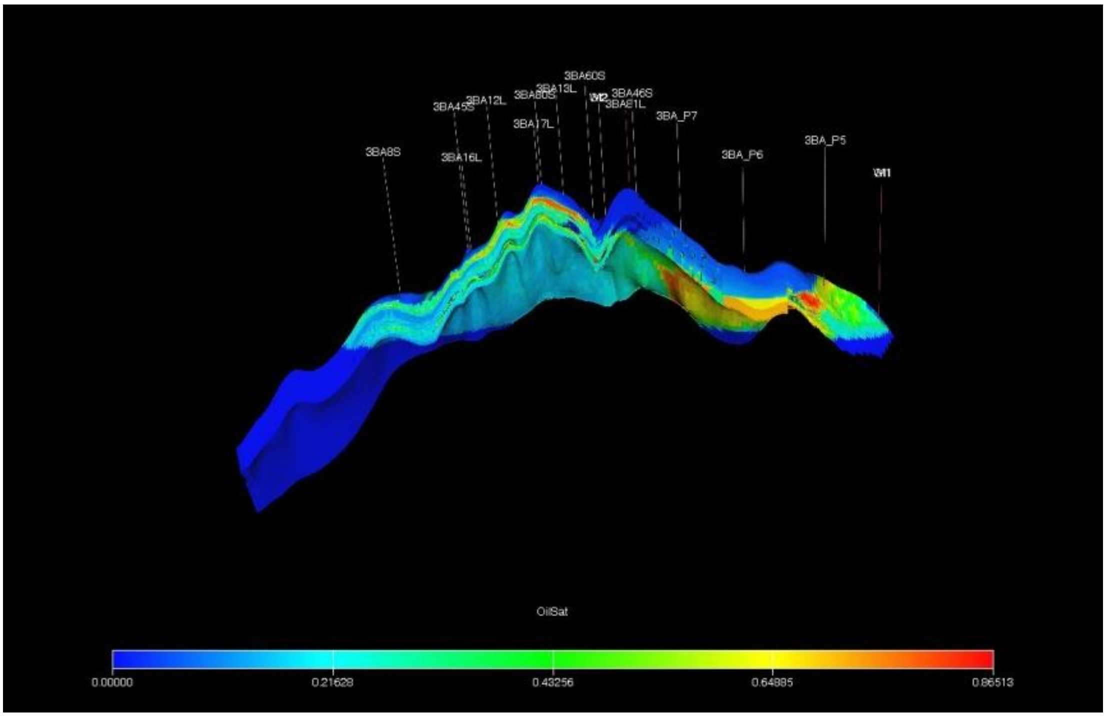

Figure 13. Initial oil saturation of real sector model

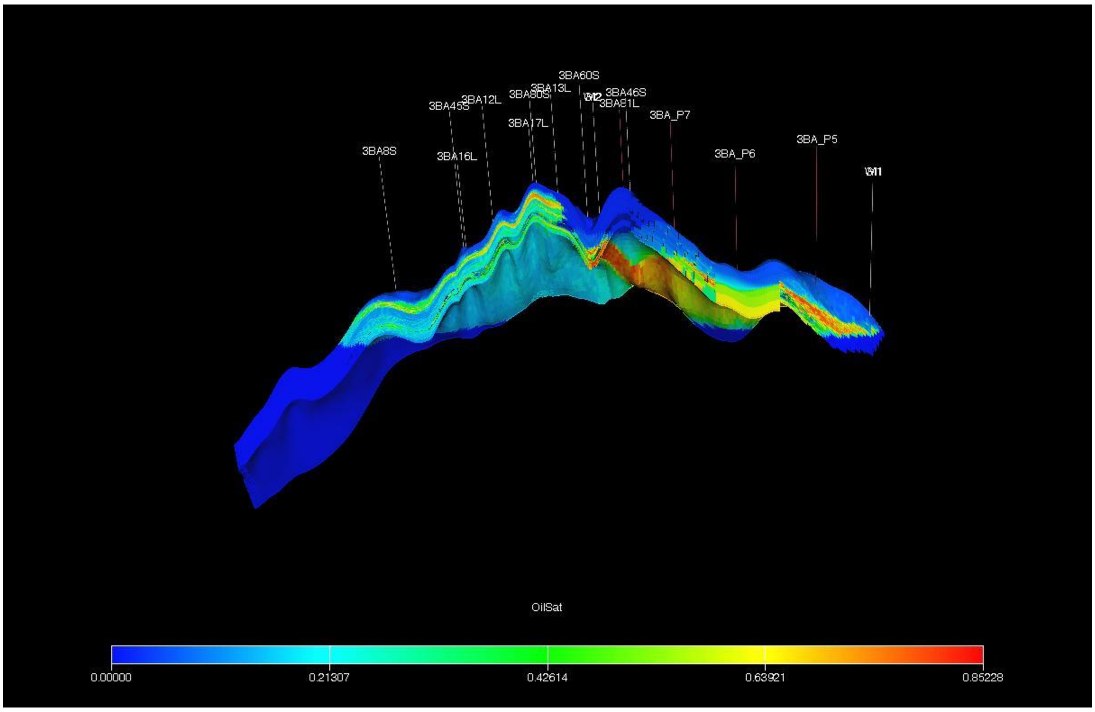

Figure 14. Residual oil Saturation of real sector model for Scheme I

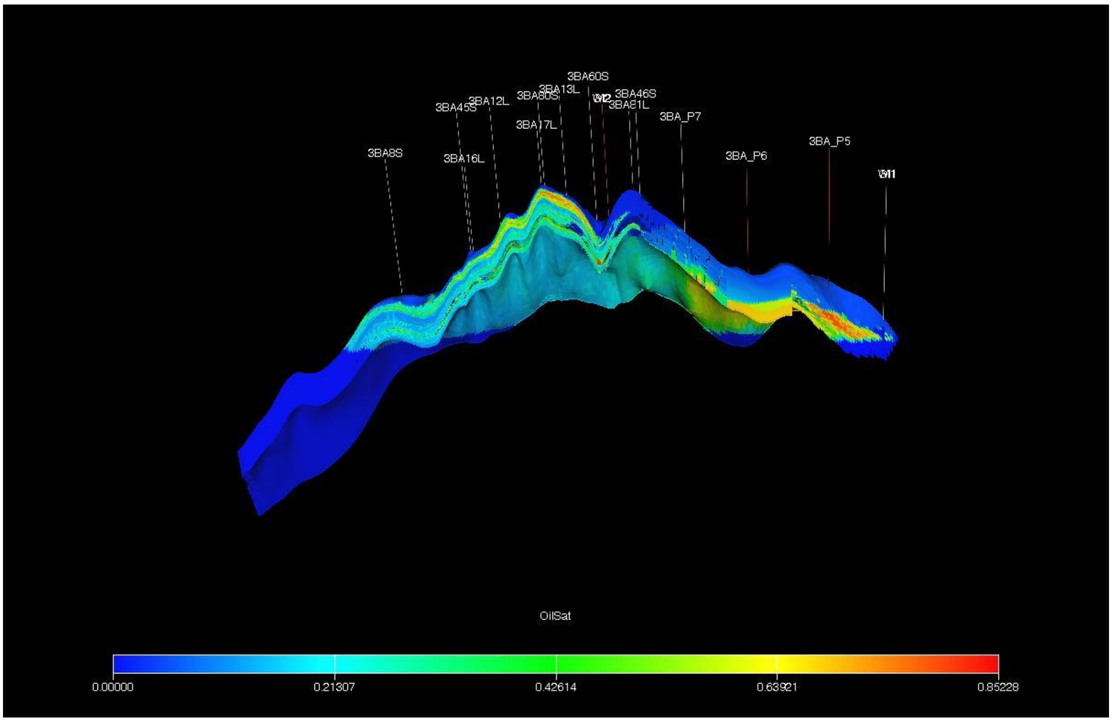

Figure 15. Residual oil Saturation of real sector model for Scheme II

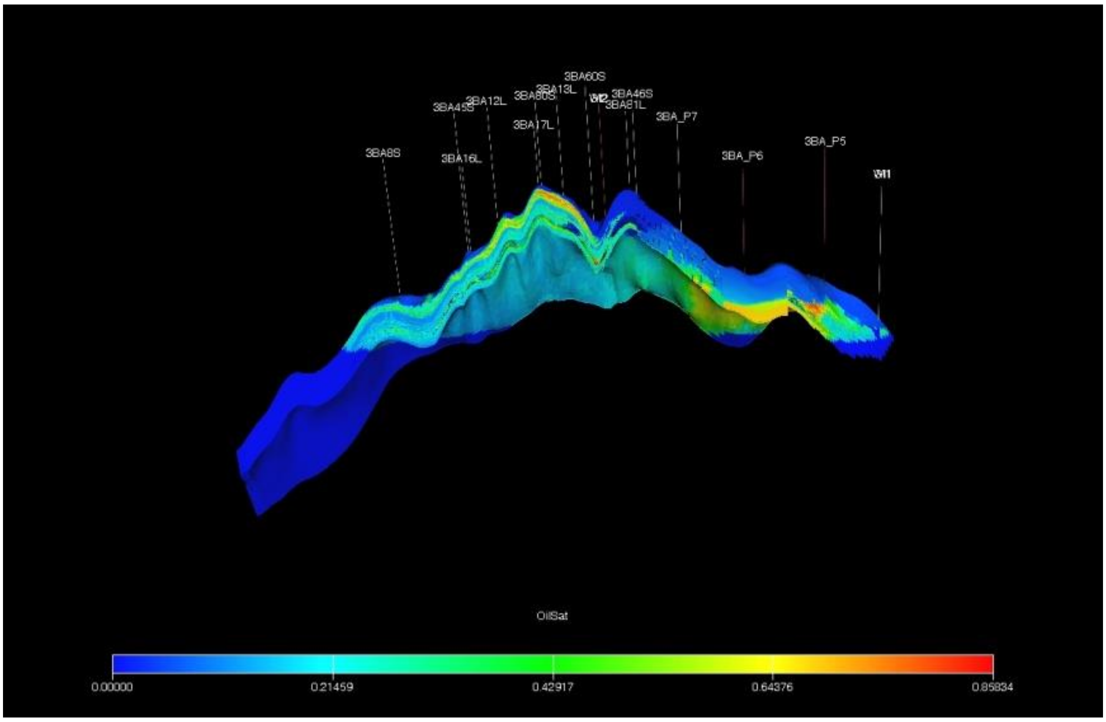

Figure 16. Residual oil Saturation of real sector model for Scheme III.

Shown in Figure 14 is the initial oil saturation for the sector model. Figures 15, 16, and 17 show the distributions of residual oil saturation obtained for Schemes I, II, and III, respectively. As it can be seen from the residual oil saturation map, Scheme I has the poorest sweep efficiency as compared to Schemes II and III. For Scheme II the sweep efficiency is improved-some of the yellow and red color change to light blue- and Scheme II leads to the improvement in sweep and displacement efficacy. In Figure 17 residual oil saturation is lower with compare to residual oil saturation in Figure 14-16 which indicate better sweep and displacement efficacy in Scheme III.

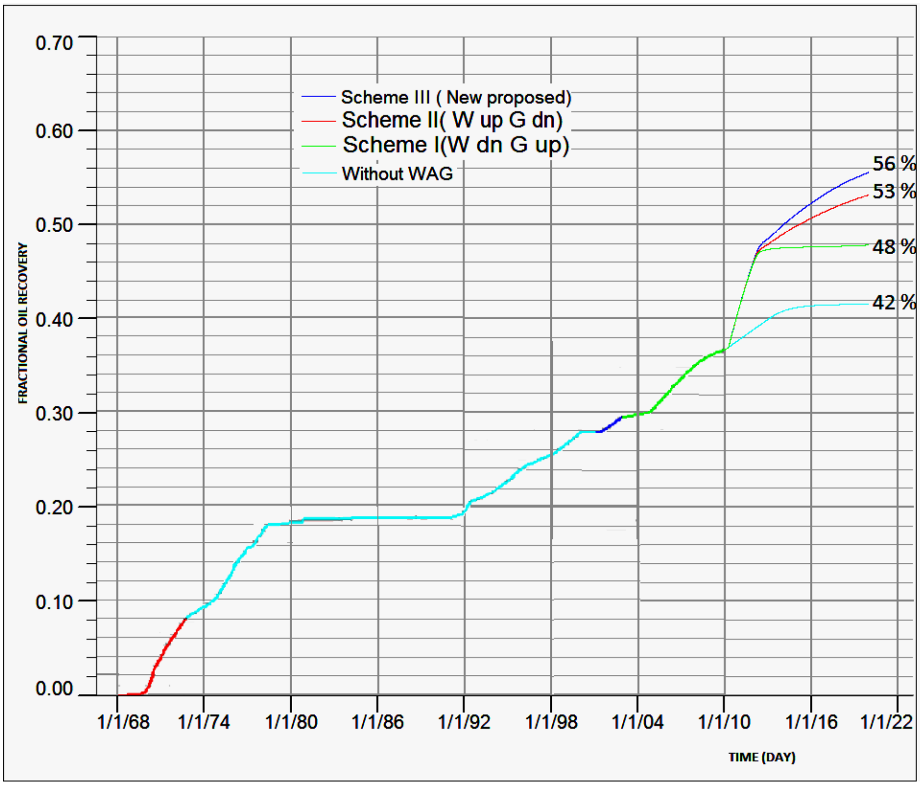

Figure 17. Fractional oil recovery for different scenario in the realistic reservoir model

The result for fractional oil recovery vs. time for each scheme is plotted in Figure 18. It is observed that Scheme III has about 14 % higher recovery factor over the base case and about 8% more than Scheme I and 3 % incremental over Scheme II results. The mechanism that caused this incremental recovery is the effect of expanding three-phase zone which is indicated in figure 17 based on residual oil saturation profile and improvement of sweep and displacement efficiency. Although not as dramatic as for the base case (without WAG injection), the impact of different WAG schemes are still significant. Even though this study is just a preliminary EOR evaluation in this field in a sector scale, the encouraging results for the proposed scheme may path the way for a much detail and thorough study of WAG implementation in this field using this scheme.

5. Conclusions

Based on this study, the following conclusions can be stated:

- The newly proposed WAG injection scheme has significant improvement of displacement and sweep efficiency and yield to higher hydrocarbon recovery for a dipping reservoir.
- Studies of modelling WAG process indicate that, in the stratified dipping reservoirs with unfavorable layering, new proposed scheme can be more efficient than up dip gas injection and down dip water injection(Scheme I) or up deep water injection and down deep gas injection (Scheme II). WAG injection is usually performed well in reservoirs with communicating layers; however, the SWAG (Simultaneous Water and Gas injection) injection can create more value in reservoirs with poor communicating layers.
- Unfavorable mobility ratio causes the WAG recovery to decrease due to early water breakthrough and increasing water cut. It may create the un-swept gas zone especially for the cases with high permeable layer at the top of reservoir.
- Injection rate should be optimized for different WAG schemes. Low or higher injection rate may cause gravity segregation or viscous fingering, which lead to lower recovery factor.
- For simple synthetic model used in this study, increasing number of WAG cycles increase the recovery but after 3 or 4 cycles the slope of recovery curve started to be stabilized, meaning that the most efficient WAG cycles are initial cycles. However for real and huge reservoir the numbers of efficient cycles depend on the displacement volume and should be optimized.
- For a realistic sector model considered in this study, incremental recovery is about 3% for Scheme III compared to Scheme II. It can be translated to a sizable incremental in the reservoirs with considerable initial oil in place. Also it should be considered that changing from Scheme I or II to Scheme III will not have additional operational and drilling costs. It can be applied with a proper operational and reservoir management plan.

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Nomenclature

WAG	Water Alternating Gas
I-WAG	Immiscible WAG
SWAG	Simultaneous Water Alternating Gas
GASWAG	Gravity Assisted Simultaneous Water and Gas injection
OOIP	Original Oil In Place

STOOIP	Stock Tank Original Oil In Place
MMP	Minimum Miscible Pressure
Φ	Average porosity
NTG	Average net to gross
kh	Horizontal Permeability
kv	Vertical Permeability
kv/kh	Permeability aspect ratio or Vertical to Horizontal Permeability
M	Mobility Ratio
RB/D	Reservoir Barrels per Day

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